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Method for Coating a Workpiece

The invention relates to a method for coating a workpiece according to the preamble of Patent Claim 1.

Numerous methods for coating workpieces are known from the state of the art. So-called thermal spray coating is a coating method in which a thermally active material is melted and then sprayed onto a surface of the workpiece to be coated, for example. Since almost all meltable materials can be used, coatings with different properties and/or functions, e.g., thermal insulation, corrosion prevention or wear prevention can be produced by thermal spray coating. In thermal spray coating, there are almost unlimited possible combinations between the material of the object to be coated and the thermally active material to be used for the coating. Depending on the heat source used, a distinction is made between various thermal spray coating methods, e.g., plasma spraying, electric arc spraying, flame spraying or high speed flame spraying. The choice of a suitable heat source and thus the proper thermal spray method depends, for example, on the material to be used for the coating, the desired properties of the coating and the respective cost.

In coating blades of a gas turbine, which are preferably made of titanium/nickel alloys, the thermally active material for the coating is preferably a thermal spray powder according to EP 0 487 273 B1. Such a spray powder according to EP 0 487 273 B1 is preferably applied to the workpiece to be coated by plasma spraying, a suitable plasmatron being disclosed in EP 0 851 720 B1, for example.

In coating workpieces with a thermal spray method, quality control of the resulting coating plays an important role. Only if the coating meets pre-specified quality criteria, can the coated workpiece pass quality control and be processed further, if applicable. According to the state of the art, destructive test methods on random samples are used for quality control. However, quality control that destroys the

workpiece is both time-consuming and cost-intensive and can be performed only on random samples.

Against this background, the object of the present invention is to create a novel method for coating a workpiece.

This object is achieved by a method for coating a workpiece according to Patent Claim 1. According to this invention, the injection process is monitored on-line by detecting properties of the particles in the spray jet and supplying them as actual values, whereby the actual values are compared directly with target values, or characteristic quantities derived from the actual values are compared with target values, and whereby, in the event of a deviation between the actual values or characteristic quantities and the pre-specified target values, process parameters for thermal spray coating are automatically adjusted by a regulator based on a neuronal network.

With the help of the present invention, thermal spray coating can be monitored on-line; in addition, process parameters for thermal spray coating can be adjusted automatically. This allows the creation of an on-line regulating system for thermal spray coating which makes the destructive test method known from the state of the art superfluous. Through the inventive method, defective coatings and complex test methods are avoided. Defects caused by manual misadjustments are prevented due to the fact that an automated coating operation is provided.

According to a preferred development of the present invention, a neuro-fuzzy regulator is used, combining at least one neuronal network and fuzzy logic rules and thus forming statistical correlations between input variables and output variables of the neuro-fuzzy regulator.

Preferred developments of the invention result from the subclaims and the following description. An exemplary embodiment of the invention is explained in greater detail with reference to drawings without being limited thereto. They show in:

Figure 1	a highly schematic diagram of a device for coating a workpiece to illustrate the inventive process;
Figure 2	the structure of a neuronal network used in the inventive process; and

Figure 3 the structure of a neuro-fuzzy regulator used in the inventive process.

The present invention is described in greater detail below with reference to Figures 1 through 3.

The invention relates to a method for coating the workpiece by means of thermal spray coating. In thermal spray coating, a meltable material is melted and sprayed in molten form onto a workpiece to be coated. Although the invention is described below for so-called plasma spraying as an example, it should not be limited to plasma spraying. Instead, the present invention may also be used with all other thermal spray coating methods. However, the invention may be used to particular advantage in plasma spraying.

Plasma spraying as such is adequately well known from the state of the art. For example, EP 0 851 720 B1 discloses a plasmatron suitable for plasma spraying. EP 0 487 273 B1 discloses a thermal spray powder which is a suitable material for coating a workpiece. For the sake of thoroughness, it should merely be pointed out that in plasma spraying, an electric arc is ignited between a cathode and an anode of a plasmatron (not shown). This electric arc heats plasma gas flowing through the plasmatron. Examples of plasma gases that are used include argon, hydrogen, nitrogen, helium or mixtures of these gases. By heating the plasma gas, a plasma jet develops, possibly reaching temperatures of up to 20,000°C at the core. The material used for the coating, e.g., the thermal spray powder known from EP 0 487 273, is injected with the help of a carrier gas into the plasma jet, where it is melted. In addition, this material, which is to be used for coating, is accelerated to a high speed by the plasma jet. The material, which has thereby been melted and accelerated, is applied to the workpiece that is to be coated, namely by spraying. A spray jet then develops, being formed by the plasma jet on the one hand and the particle jet of the molten material on the other hand. Particles of material strike the surface of the workpiece to be coated with a high thermal and kinetic energy and form a coating there. Depending on the parameters of the spray process, the desired properties of the coating develop.

As already mentioned, the coating process depends on various parameters of the coating process, although thermal spray processes such as plasma spraying have already been well researched. The properties of the resulting coatings are subject to great fluctuations, even with seemingly constant parameters of the coating operation. The complex relationships between the process parameters and the properties of the resulting coating are responsible for this. The coating process is therefore highly sensitive with respect to fluctuations in coating procedure.

It is within the scope of the present invention to monitor and analyze the spray process and for the process parameters for plasma spraying to be adjusted automatically via a regulator, whereby the regulator comprises at least one neuronal network.

Monitoring and analysis of the spray process are performed on-line. Monitoring and analysis of the spray process are explained below with reference to Figure 1. Figure 1 shows, in a highly schematic form, a spray jet 10, which is established in plasma spraying. The spray jet 10 is monitored visually with a camera 11, which is embodied as a CCD camera in the exemplary embodiment illustrated here. The image picked up by the camera 11 is sent to an image processing system (not shown in detail). In the image processing system, properties of the visually monitored spray jet are ascertained from the information acquired by the camera 11.

For example, Figure 1 shows an analysis pattern 12 for analyzing the data on the spray jet 10 acquired by the camera 11. For example, it can be deduced from Figure 1 that the camera 11 detects properties of a plasma jet 13 as well as properties of a particle jet 14. In the exemplary embodiment shown here, the camera detects a luminance distribution of the plasma jet 13 and a luminance distribution of the particle jet 14. In the image processing system, contour lines having the same luminance are ascertained from these luminance distributions. According to Figure 1, ellipses 15 are drawn on such contour lines of the same luminous intensity. This is done for the plasma jet 13 as well as the particle jet 14. The ellipses 15 drawn in the contour lines have characteristic geometric quantities. These characteristic geometric quantities of the ellipses 15 are semi-axes a and b about the center of gravity of the ellipses, which can be identified by the coordinates Sx and Sy in Figure 1. The properties of the spray jet and ultimately the properties of the coating formed in the spraying process can be deduced unambiguously from the characteristic data on the ellipses 15. It should be pointed out that other properties of the spray jet can also

be detected and analyzed visually. Instead of or in addition to the luminance distribution, a particle temperature and/or particle velocity and/or particle size of the spray jet can also be monitored. These properties may also be used to determine the properties of the coating thus formed.

The characteristic geometric quantities of the ellipses 15, which are determined from the visual monitoring of the spray jet and correspond to the properties of the spray jet 10, are compared with pre-specified target values for these properties and/or pre-specified characteristic quantities of the ellipses. If a deviation from the pre-specified values (target values) is detected for the properties (actual values) of the spray jet, there is an automatic adjustment of the process parameters for plasma spraying by a neuro-regulator and/or neuronal network.

As already mentioned, the regulator for performing the inventive coating process is based on a neuronal network. Figure 2 shows as an example such a neuronal network 16 consisting of two layers 17 and/or 18 of neurons 19 and/or 20. The neuronal network 16 according to Figure 2 is a so-called feed-forward neuronal network.

Each neuron 19 and/or 20 of the two layers 17 and/or 18 of the neuronal network 16 in Figure 2 has an input signal a_j^{l-1} and an output signal a_i^l, where there is a linkage via weights $w_{i,j}^l$ and a bias b_i^l. As Figure 2 shows, the neurons 19 of the first layer 17 have a nonlinear, i.e., sigmoidal, transmission function but the neurons 20 of the second layer 18 have a linear transmission function.

The so-called backpropagation algorithm is used for training of the neuronal network 16 illustrated in Figure 2. An output vector for the 1st layer of neuronal network 16 is calculated here from the input signals using the transmission function, the weighting matrix and the bias vector. It then holds that:

$$a_i^l = f\left(\sum_{j=1}^{n^{l-1}} w_{i;j}^l a_j^{l-1} + b_i^l\right)$$

To calculate a_i^l it is first necessary to ascertain the unknown weights and the unknown bias. To this end, the network is trained with a plurality of data records comprising input data x_i, e.g.:

$$a_i^0 = x_i$$

and also comprising desired output data d_k. At the start of training, the weights and the bias are set at random values. To ultimately determine their current values, many iterations are necessary to minimize the following error function.

$$E = \frac{1}{2}\sum_{k=1}^{n^2}(d_k - a_k^2)^2$$

According to the backpropagation algorithm, the updating of the weights and the bias follows the descending gradient of the error function, whereby it holds that:

$$\Delta w_{i;j}^l = -\frac{\partial E}{\partial w_{i,j}^l}; \quad \Delta b_i^l = -\frac{\partial E}{\partial b_i^l}$$

Use of the sigmoid-like transmission function given below

$$f(\sigma) = \frac{1}{1+e^{-\sigma}} \quad \text{whereby} \quad \sigma = \sum_{j=l}^{n^{l-1}} w_{i;j}^l a_j^{l-1} + b_i^l$$

in combination with the adjustment of the following abbreviated formula

$$\delta_k^2 = a_k^2(d_k - a_k^2)(1 - a_k^2)$$

$$\delta_j^l = a_j^2(1 - a_j^2)\sum_{k=l}^{n^l} w_{j,k}^2 \delta_k^2$$

and the introduction of a so-called learning rate λ ultimately results in the following relationship for determination of the weights and bias in the learning step k:

$$w_{i,j}^{l}(k) = w_{i,j}^{l}(k-1) - \lambda a_{j}^{l-1} \delta_{j}^{l}$$
$$b_{i}^{l}(k) = b_{i}^{l}(k-1) + \lambda \delta_{j}^{l}$$

It should be pointed out that there are many variants of the backpropagation algorithm that differ essentially through the convergence criteria.

Using such a neuronal network 16, a relationship can be established between the process parameters for thermal tips and the required coating properties. Such a neuronal network is an adaptive, error-tolerant learning system. Use of such a neuronal network in a regulator for the coating process allows especially good process control.

As already mentioned, neuronal networks are adaptive systems which can learn patterns of data volumes. Neuronal networks are thus capable of recognizing the learned patterns in unknown data volumes, where extrapolations and interpolations are possible. The neuronal network may, however, recognize only those patterns that correspond to precisely the learned patterns.

In the exemplary embodiment in Figure 2, the neuronal network comprises only two layers of neurons. However, it is also possible to use a neuronal network having a greater number of layers. For example, a neuro-fuzzy regulator may be used, combining a neuronal network and fuzzy logic rules together with a larger number of layers. This is explained below with reference to Figure 3.

Figure 3 shows the structure of a neuro-fuzzy regulator 29 used according to a preferred development of the present invention, having a total of four layers of neurons in the example of Figure 3, namely a first layer 21 with neurons 22, a second layer 23 with neurons 24, a third layer 25 with neurons 26 and a fourth layer 27 with neurons 28.

Neurons 22 of the first layer 21 form an input layer of the neuro-fuzzy regulator 29 and serve to implement the so-called fuzzification. Neurons 28 of the fourth layer 27 form an output layer of the neuro-fuzzy regulator 29 and serve to implement the so-called defuzzification. Neurons 24 of the second layer 23 and neurons 26 of the third layer 25 form intermediate layers (hidden layers) of the neuro-fuzzy

regulator 29 and serve to implement so-called fuzzy inference.

In fuzzification in the first layer 21 of the neuro-fuzzy regulator 29, the input variables a_1, a_2 through a_{na} of the neuro-fuzzy regulator 29 are converted into fuzzy variables processable by fuzzy inference. Input variables a_1, a_2 through a_{na} are so-called crisp input variables which are converted by fuzzification into uncrisp fuzzy input variables $m^a_{l,k}$, $\alpha^a_{l,k}$ and $\beta^a_{l,k}$. The uncrisp fuzzy input variables are sent as input variables to the fuzzy inference, namely the second layer 23. In fuzzy inference, these fuzzy input variables are processed via linguistic rules and fuzzy operators, in particular via minimum operators g_1, g_2, g_3 through g_{ng} and/or maximum operators h_1, h_2 through h_{nh}, where the third layer 25 outputs fuzzy output variables $m^b_{j,i}$, $\alpha^b_{j,i}$ and $\beta^b_{j,i}$ as the result. The fuzzy output variables are again so-called uncrisp variables. These uncrisp output variables are converted to crisp output variables b_1 through b_{nb} of the neuro-fuzzy regulator 29 by defuzzification, which is implemented with the fourth layer 27.

In such a neuro-fuzzy regulator 29, the relationship between the input variables a_1, a_2 through a_{na} and the output variables b_1 through b_{nb} are pre-specified for the neuronal network before the learning in the form of linguistic fuzzy rules. However, with the neuronal network 16 of the exemplary embodiment in Figure 2, the relationship between the input variables and output variables is unknown and is automatically compiled and/or learned by the neuronal network 16. The neuronal network 16 of the exemplary embodiment in Figure 2 is a black box, so to speak. This is avoided with the neuro-fuzzy regulator 29 of the exemplary embodiment in Figure 3. By training the neuro-fuzzy regulator 29 of Figure 3, the relationship between the input variables a_1, a_2 through a_{na} and the output variables b_1 through b_{nb} is optimized. However, the structure of the neuro-fuzzy regulator 29 is preserved, so that transparency is increased and a diagnosis is made possible. Since the neuro-fuzzy regulator 29 is capable of processing uncrisp values, it is more error-tolerant than the exemplary embodiment of Figure 2.

In the exemplary embodiment shown in Figure 3, the neuro-fuzzy regulator comprises four layers of neurons. However, it is possible to use a neuro-fuzzy regulator having a greater number of layers. With such a higher number of layers, the number of fuzzy inference mapping layers arranged between the input layer and the output layer would be increased.